Advanced Avionics Applications Simulation Platform (AAASP) for Accurate Aircraft Systems Simulation

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Abstract—**A persistent problem for Aircraft Manufacturers has been the difficulty in carrying out accurate and robust simulations of the complete aircraft power network, while including numerous models from a variety of individual equipment suppliers. Often the models are of variable or low quality, with ill-defined parameters or behavior, and in many cases of the wrong level of abstraction to be appropriate for large scale network simulations. In addition, individual equipment suppliers often provide poor models for network integration, with a common issue being low robustness of models leading to lack of convergence, excessive simulation times and delays in development due to the need for rework and extensive testing of these models.**

In order to address this specific issue a complete library of power electronic system models for Aerospace applications has been developed that encompasses the range of functions from elementary components (passives, devices, switches and magnetic components), intermediate building blocks (rectifiers, inverters, motors, protection devices) and finally complete system models (variable frequency starter generators, power converters, battery and storage elements, transformers). These models have been developed in partnership with several key aircraft equipment suppliers and in partnership with Airbus to ensure that the resulting models are complete and robust. Specific equipment models were also developed in this library including permanent magnet generators, synchronous machines, environmental control systems, wing ice protection systems, power electronic modules and advanced power protection systems. The specific models have been validated against reference and measured data to ensure that they are consistent and accurate.

This paper will describe the techniques used to achieve more robust models, using model based engineering, the integration of specific equipment models into the complete aircraft network and the validation of the behavior against measured results. The paper will provide the results of a complete aircraft power network highlighting how the individual models are integrated into the overall network model and the inherent robustness ensure effective, accurate and robust simulations.

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1. INTRODUCTION

The overall aim of the European Union Clean Sky project [1] is to demonstrate the substantial performance and the economic benefits of implementing more electric aircraft technologies. For electrical and electronic systems in aircraft, it is becoming an intrinsic part of the design process for modelling and simulation to allow validation of the design of sub-systems connected to the aircraft electrical network, and the network itself.

It has become incumbent on Aircraft suppliers and manufacturers to ensure that the electrical network can be operated in a safe and reliable manner.

In this project, the approach was taken that if a comprehensive library of models could be developed in conjunction with a suite of validation and simulation tools, then this process could not only be made more streamlined, but also lead to an overall reduction in the design time, with a potentially significant benefit to both the efficiency and accuracy of the final product with regard to the detailed specification of both equipment and aircraft systems.

In order to achieve this a multiple domain simulation platform was required to be used and while there are in fact numerous potential options to implement such a model library, the Saber software (SaberRD) [2] was mandated to be used for this project. Alternatives do exist for modelling of electronic systems including Pspice [3], PSIM [4], Variations of the SPICE platform originally developed at the University of Berkeley for IC simulation [5], SystemVision [6], Modelica [7][14] and Matlab [8], however it is true to say that Saber has significant advantages in this context and application.

The purpose of the project is to develop a set of models, libraries, scripts and test circuits to enable the complete analysis of the Aircraft Power System at different levels within the context of the proposed Advanced Avionic Applications Simulation Platform (AAASP) as shown in Figure 6. In order to complete this, there needs to be a comprehensive set of models that can be used in a generic sense, or parameterized by a customer to represent specific equipment.

The overall strategy of the work plan is to take a two level approach to completing both the full set of generic models for general release, and also the individual test case demonstrators in a timely manner. To achieve these goals, the scheduling of the specific test cases will be defined so that the generic components required for each test case will be developed first and then while they are being tested in the test case, the next set of generic models will be being developed for the next test case. In addition to this, the sets of scripts, functions and test circuits will be developed and validated with each test

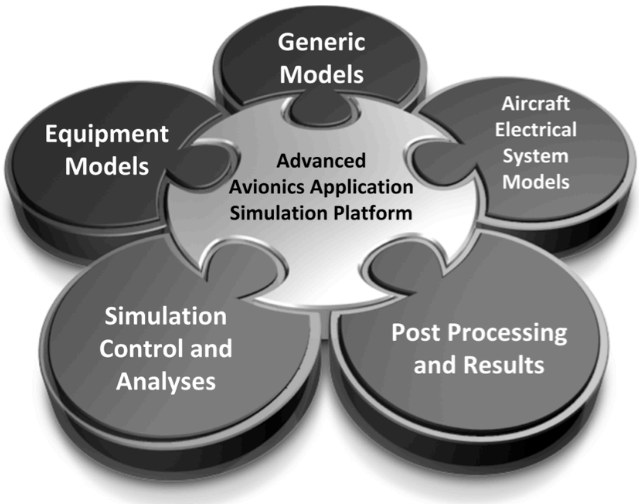

Figure 1: Advanced Avionics Application Simulation Platform

2. AIRCRAFT ELECTRICAL POWER SYSTEMS

The sheer complexity of the aircraft power system, as well as the competing requirements for high level system analysis and detailed equipment design, means that a structured approach is necessary to ensure that the simulation results are accurate, consistent, and the models robust enough to operate under a wide variety of conditions and simulation tests.

Historically, the fundamental aspects of aircraft electrical power systems have been assessed based on the fundamental definitions in MIL-STD-704 [9] and related international standards, but also in the more recent updated electrical power specifications in use by individual aircraft manufacturers. Many of these more modern aircraft specifications take into account the concepts and requirements of More Electric Aircraft (MEA). Many of the aircraft specific requirements can be considered as a “superset” of the original MIL-STD-704 requirements, and it therefore often remains as a baseline starting point. The major power system categories are:

- 115V AC Systems (nominally 400Hz)
- 230V HVAC Systems (nominally 400Hz)
- HVDC Systems (under 600Vdc)
- LVDC Systems (28Vdc)

A “standard” Aircraft System can therefore be deconstructed into groups of standard element and these are described in more detail in this paper. A typical modern aircraft will have HVAC and HVDC voltage busses at power levels up to 1MW. There is a power distribution centre, which contains switches to control the flow of power to the various sub-systems, but also incorporates protection and circuit breakers. Connected to the power centre are three main types of power converter (AC/DC, DC/DC, DC/AC and AC/AC converters). The hierarchy and configuration of power conversion will vary from aircraft to aircraft, however it is clearly the case that there may be chains of converters from the high voltage aircraft bus, all the way to individual devices operating at much lower voltages.

3. MODELING APPROACH

The model library requires an appropriate level of model to provide the best trade-off between simulation accuracy and performance. It is a general principle that the more complex the system model is, the longer the time required to complete simulations, and so a practical judgment needs to be made as to the most useful level of modeling to be undertaken.

A typical Aircraft power System could be modeled at a number of levels from a very high level (architectural) down to detailed component level. Both of these extremes are often not appropriate for power system analysis, although have uses in certain cases.

The two most useful modeling levels for the analysis of modern aircraft power systems are the functional and behavioral levels. The functional models consist of models that do not include switching behavior and are therefore used for rapid simulation of system power, dynamics and frequency response behavior. Power converters would be modeled using averaged models, and the topology will reflect the complete system, with the ability to observe dynamics and power transfer such as those analyzed in [10]. Detailed effects such as Inrush current and voltage transients would also be observable, however harmonic and other switching behavior would be ignored. The key requirement of the functional model is to ensure system robustness, steady state power consumption, network stability studies and the validation of the network logic and control characteristics. Simulations times are generally very fast, relative to a switching simulation.

Behavioral models would in contrast include switching behavior and would therefore allow detailed analysis of network stability and also power quality. Harmonics of line currents and voltages can be simulated using behavioral models, however in most cases, the power electronic devices (MOSFETs, IGBTs and Diodes) would be represented using idealized models, rather than detailed component models. These simulations would be in general slower than functional models, but have a greater degree of switching cycle accuracy.

While it is often the case that a simple model will simulate quite adequately, when it is placed in a larger system, even simple models can have convergence or accuracy issues. This is a vital aspect of the project where even simple generic models need to be refined to ensure that they will be robust under a wide variety of simulation conditions and test scenarios. For example, even the basic power diode needs to be taken care with to ensure that a simple piece wise linear approximation does not cause convergence issues.

The models of the equipment and system were developed in three phases, Preliminary, Consolidated and Laboratory Unit Acceptance, with increasing levels of accuracy and consistency with real equipment or system tests. The function of the preliminary models is to establish the correct basic operation of the equipment, the consolidated models are designed to demonstrate that the equipment should pass the requisite aircraft specification tests, and the laboratory unit acceptance models should also demonstrate consistency with the real equipment.

The equipment and system models require a range of tests to be undertaken to evaluate the steady state power, power-up and transient performance including switching, power-up and inrush, and finally power quality including monitoring the current and voltage harmonics.

4. Key Challenges

The major challenge that faces the aviation industry in addressing these fundamental problems in the design process is due to the lack of a "Simulation Platform" specifically designed to handle the challenges inherent in complex avionic power systems. As we have discussed, it is not just the understanding of modeling to create a model, but also the ability to understand the simulator and the simulation processes to achieve a robust and accurate model. As the scale of the electrical system has increases and will continue to increase for future more electric aircraft systems, the complexity and scale of the simulation will also increase. This has a serious implication for the ability of the simulation platform to be able to cope with this increase in scale and complexity, particularly with the ability of the simulation to be completed.

Currents solutions tend to use default generic model libraries (often developed for the semiconductor or other industries rather than being design with avionics in mind) and default analysis tools that may have been adapted to address avionic designs but that cannot necessarily cover the difficulties raised by modern more electrical aircraft architecture. This has generally been because these solutions have been based on available tools and limited models which were not developed to take into account the particularities of the Avionic domain (huge and complex systems, multi-domain systems, multiple switching devices, and multiple networks. The other technique commonly used is to develop models for a specific region of operation such as power semiconductor compact models [15-18],[23].

The result is that a simulation methodology that is based on the available tools today will often work for the development of specific virtual equipment models but often fails at the system integration phase of the complete electrical network design. The accumulation and interaction of model "weakness" which only occur at the integration level can dramatically impact the global robustness of the final design making the simulation at system level very difficult. As a consequence, confirmed by the outcomes from previous projects, integration phase is a critical task. All these requirements are pushing to a "Model Based Engineering" (MBE) approach [12],[13],[19-22],[24] where the intelligent use of models and simulations become an inherent part of a validation and verification cycle. There are a plethora of power simulation libraries for almost every simulation software tool available, however they tend to be targeted at a specific area or level of modeling, in contrast, this library has been developed to cut across all levels of the aircraft power system.

5. Electrical Network Modeling

The primary objective of this part of the project was to demonstrate a complete electrical network system simulation. The role of the equipment models is to enable European Aircraft Equipment Manufacturers to create an overall electrical system model quickly and easily that can be simulated in SaberRD. The models must be inherently robust and with parameters appropriate for Aircraft Electrical System Simulation. A complete library of network elements including contactors, feeders, filters and impedances was developed in conjunction with the major elements for a complete aircraft network including generators, loads, transformers, fuses, protection devices, power converters and transformers. A preliminary electrical network model has been completed and demonstrated. This enables early testing of the network software and test scripts, and first evaluation of network robustness.

The Network model necessitated the completion of a full set of building block models enabling the initial network model to be constructed and simulated. The Network model itself was constructed using multiple sheet schematics enabling a single top level network displaying the relationships between power bus bars as shown in Figure 2. Each bus bar has a separate sheet with generators and loads. Contactors were designed in such a way that scripts could be used to energize or isolate sections of the network and demonstrate start-up or dynamic load scenarios.

A critical aspect of modeling is being to use these models to predict the performance of the design and also to optimize the overall system in terms of specific characteristics. This requires the use of system level optimization techniques such as Pareto fronts and evolutionary algorithms, which are also only practical where the models are efficient and fast as described in [25]-[27].

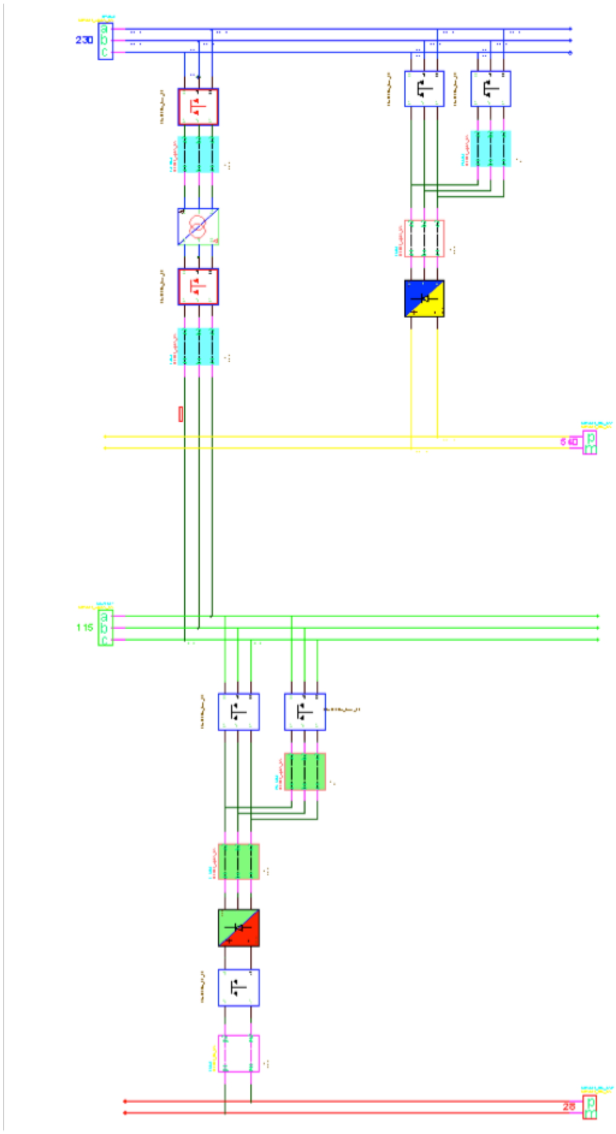

Figure 2: Aircraft Electrical Network Test

With the network model in place, including a separate sheet for each type of load array (DC, VDC, AC and HVAC), the Variable Frequency Starter Generator (VFSG) could be started up using a mechanical rotating shaft input and the output voltage observed as the various bus bars were energized. In this case the main HVDC voltage was the point of regulation and when the main AC busses were switched in, the resulting voltage transients could be observed on the HVDC bus as shown in Figure 3.

The contactor, feeder, source and load models also include a range of monitoring variables such as voltage, current, power, VA, THD etc, which allow the user to monitor the behavior of the network at any point, for example, in Figure 4, the power is shown in the VFSG as two separate HVDC loads are turned on in sequence, showing the transient behavior of the power in each load and in the VFSG (generator).

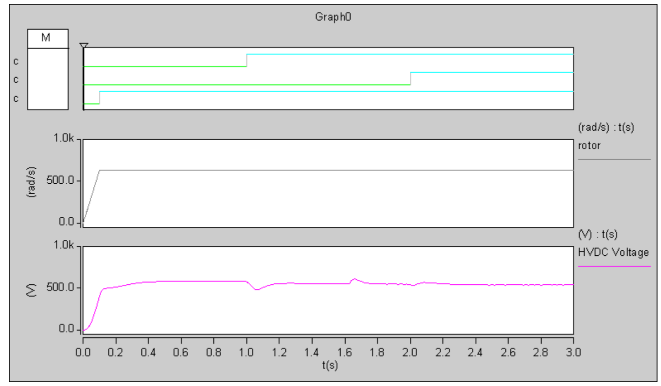

Figure 3: VFSG output - HVDC Busbar

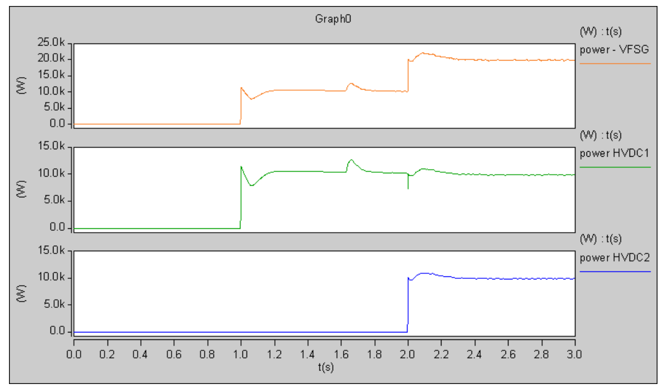

Figure 4: Power at VFSG and HVDC Loads

6. MODELING POWER ELECTRONIC MODULES

In order to provide a complete library of building block models at all levels an intermediate stage of models was developed that included power electronic modules (rectifiers, converters, inverters), transformers (3 phase, Delta-Delta, Wye-Wye, Delte-Delta-Wye, Single Phase), Solid State protection Devices, Machines, Generators, Motors and Loads. For example, a three phase inverter module with closed loop PWM control was developed to enable designers to either construct a model usig building blocks of each element (power electronics, PWM generator, control blocks) to create a custom design, or implement a complete model with fully integrated control that could be easily parameterized. For example a three phase inverter power electronics module model was developed, with associated PWM Drivers and this was tested with a fixed sinusoidal control block, and then integrated into a closed loop model to drive a synchronous machine.

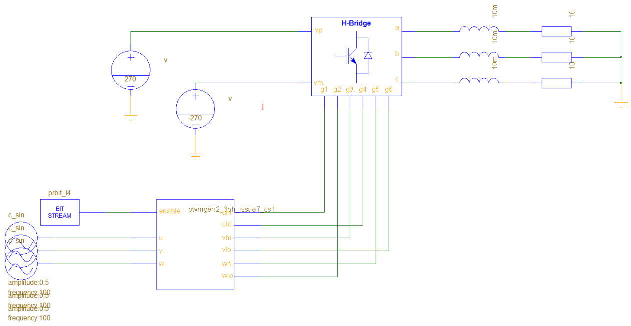

Figure 5: Inverter Power Electronics Module

When this was tested, the resulting voltages and currents can be seen to be completely consistent with predicted values for an LR load, typical of an inductive motor load.

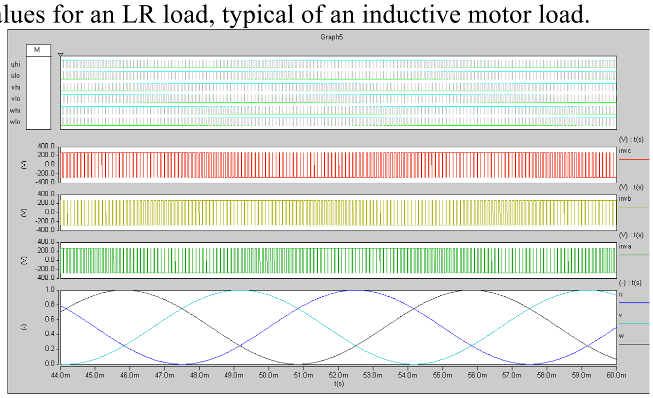

Figure 6: Control, Voltage and Current Waveforms

This was then integrated with the synchronous machine model and a closed loop (PI) controller to output a demand power of in this case 10kW.

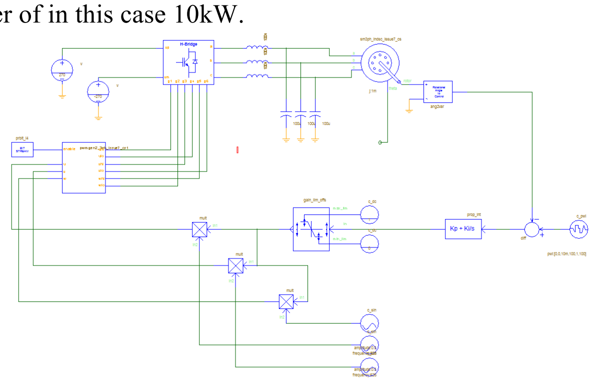

Figure 7: Closed Loop Control with Power Demand

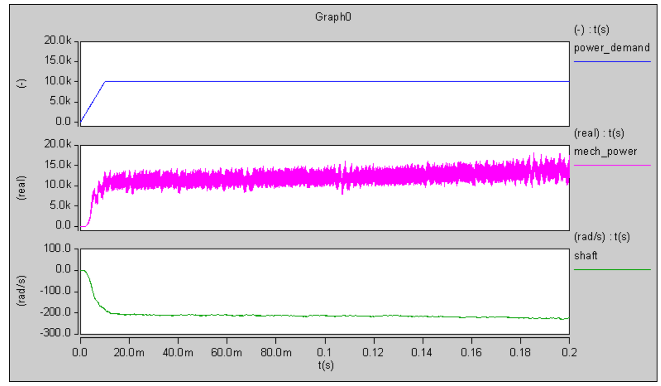

Figure 8: Output Power and Shaft Speed

These initial results demonstrate not only the basic behavior of the models but also the ability to investigate the performance and effect of key parameters on the behavior of the models in isolation and in the network as a whole.

7. Model Based Engineering

As the models become more complex, methods are required to ensure that the development of these models are controlled, consistent and correct. As most of the modeling languages in current use (MAST, Modelica, VHDL-AMS, Verilog-AMS, C, Matlab etc) are ASCII code based, the choice for the hardware designer is often a difficult one, as the tools tend to be aimed firmly at the software development community rather than the hardware design community.

In order to address this, there have been efforts to develop graphical modeling tools to mitigate these effects and to make model development more intuitive for hardware engineers (Simulink in Matlab is a good example of this, as are the various schematic editors in circuit simulators). One example of this is the model development toolkit in the Saber software, however this is very model specific and not general purpose. Paragon was developed at the University of Arkansas [15]-[22] primarily to allow model development in a language agnostic methodology and has been used in this work as a way of ensuring that the complex interdependencies between individual models at all levels are tracked through and checked in all the model validation steps of this work.

For example, all the elementary models in the AAASP library (passives, semiconductor devices etc) were used in the intermediate library (power electronic modules, transformers, power converters) and finally the complete models at the highest level then used models that had previously been validated in the other libraries.

For example, consider the model of a variable frequency starter generator with HVDC point of regulation as shown in Figure 9. This has individual models already validated in the intermediate library (filters, controller, rectifier) and in particular the generator model with a field winding control loop, based on the HVDC measurement of the output. It should be stressed that this is NOT the schematic of the model, but is a topology defined in the modeling tool, where individual equations, parameters and connections dynamically reflect changes in the model topologies at all levels.

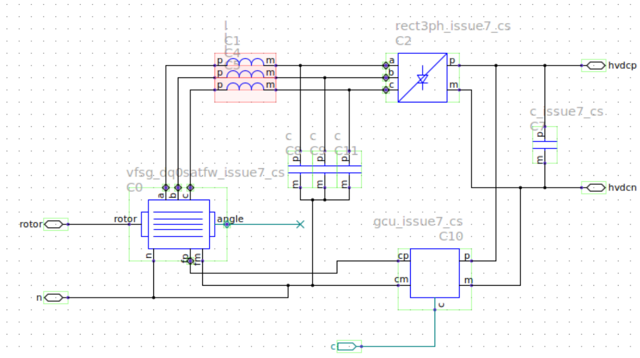

Figure 9: VFSG Hierarchical Model

When the VFSG generator model was tested in a simulation, using a dynamic load change, the resulting behavior can be seen, with the effect of the control loop to keep the HVDC voltage regulated within limits as required.

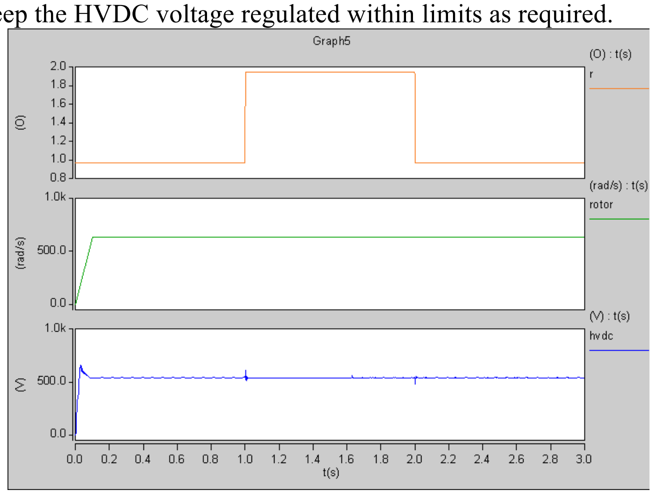

Figure 10: VFSG Dynamic Load Test

With the completion of the Elementary, Intermediate, Complete, Network and also specific test-bench models, there were more than 100 separate models implemented in the new library and this is now being integrated into the SaberRD software for wider release and dissemination. The complete library structure within SaberRD is shown in Figure 11, where each model has a library entry, symbol, test circuit and documentation.

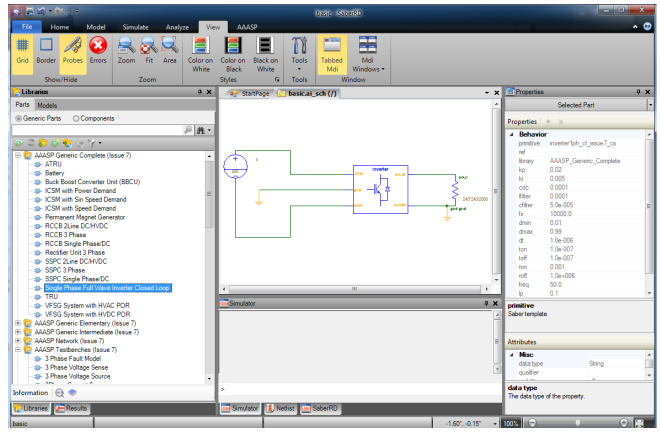

Figure 11: AAASP library Integration

8. Multiple Mode Magnetic Models

In order to achieve the correct dynamic and non-linear behavior of the electro-magnetic models including motors, inductors and transformers, a general purpose magnetic model topology was developed that included multiple modes of operation for the non-linear magnetic material models. The models could switch between linear (useful for system level and frequency response analysis), non-linear (no hysteresis, but including saturation effects), fully hysteresis (complete BH response with frequency effects and eddy currents) and finally hysteresis with thermal effects. It is beyond the scope of this paper to go into detail of the individual effects, however these have been described in detail in previous work [29-33].

The approach taken in this library has been to integrate as many effects as possible into a single model so that the user can define which level of model is required without having to fundamentally change the overall circuit, therefore simplifying the construction of the circuit, and ensuring that the top level design can be used with simple models to check the overall impact on the network, an intermediate model with saturation to evaluate the effect on inrush currents for example, and finally the detailed BH curve effects on THD (for example) with the highest level of detail model.

For example, if a line impedance was modeled with a "type 1" model, including saturation, the resulting behavior can be seen as shown in Figure 12 and Figure 13. These were created from the same circuit, simply by setting the model "type" parameter to 1 or 2 respectively (type 0 is linear).

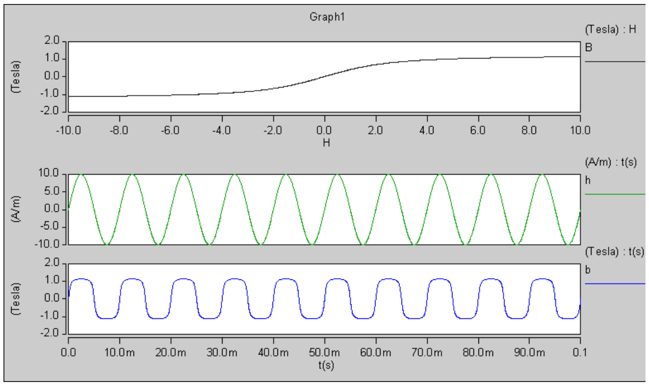

Figure 12: Saturation Effects in Level 1 Model

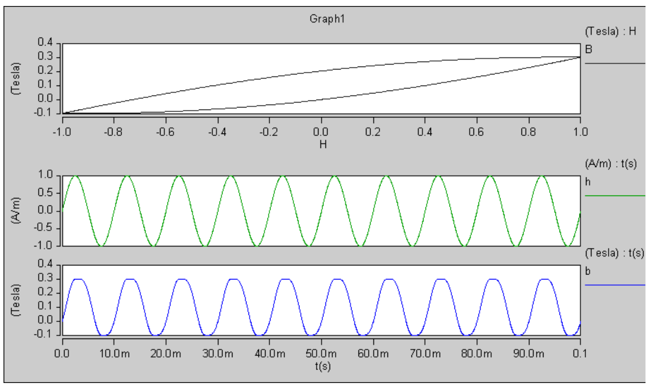

Figure 13: BH Curve details in Level 2 Model

9. FULL NETWORK SIMULATION

The objective of the specific equipment models work package was to provide a set of models, schematics, symbols and tests to enable equipment level simulations to be undertaken at functional and behavioral level in SaberRD. The role of the equipment models is to enable aircraft equipment manufacturers to quickly evaluate an overall system and to provide a starting point for engineers to build a model quickly and easily that can be simulated in SaberRD. The models must be inherently robust with parameters appropriate for Aircraft Electrical System Simulation, and in order to facilitate that, the AAASP models have been rigorously tested for robustness on a wide range of tests (38 in all) ranging from simple checks of parameter default values through to non-linearities and convergence analysis. The various equipment models were integrated into the overall network simulation and a "control panel" schematic created with all the individual contactor control signals to enable a full system simulation to be defined from this one place. The various network simulation sheets can be seen in Figure 14, with the control panel in the top right hand window.

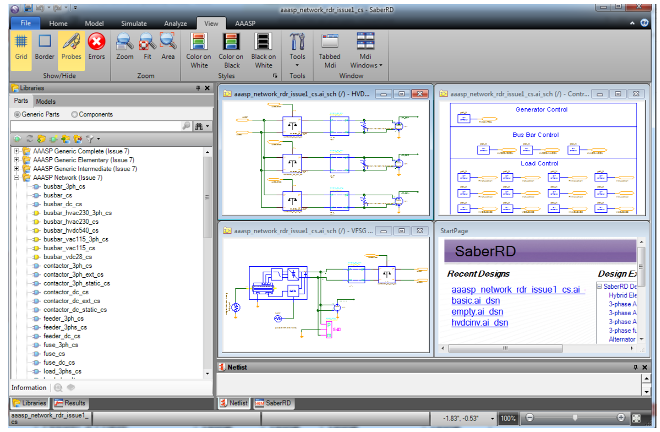

Figure 14: Full Network Simulation

This is an important aspect of the new approach where the testing of individual equipment models (such as a PMG or VFSG) can take place outside the network simulation), however the same test criteria can be used by the network integrator to test the same model in the aircraft network model to ensure that the model will simulate, the behavior will be correct (and accurate) and the equipment will be within the specification limits defined by the aircraft manufacturer.

When the full Network including various loads on all the major power busbars was completed (HVDC/DC/HVAC/AC), the resulting waveforms are shown in Figure 15. The HVDC bus is started initially, and then the DC, HVAC and finally AC busbars are energized in turn. Once each busbar is live, then a sequence of loads is initiated as can be seen in the results, with the transient behavior shown on the HVDC voltage, and also the overall power through the main contactor up to the full load of more than 100kW. Data converters from HVAC to AC using transformers, and HVDC to DC using DC/DC power converters are also included in this overall system simulation. For reference, the 5s real-time simulation, took 84s for the complete network including those power electronic modules on an i7 based PC, although this is not intended to demonstrate any comparative performance, simply an indicator of the time taken to run this type of simulation on this type of platform.

Simulations of specific equipment models such as the VFSG, Generator and machine models were undertaken and also analysis completed using this library of ECS (Environment Control System), WIPS (Wing ice protection system in anti-ice and de-ice modes) and solid state protection circuits.

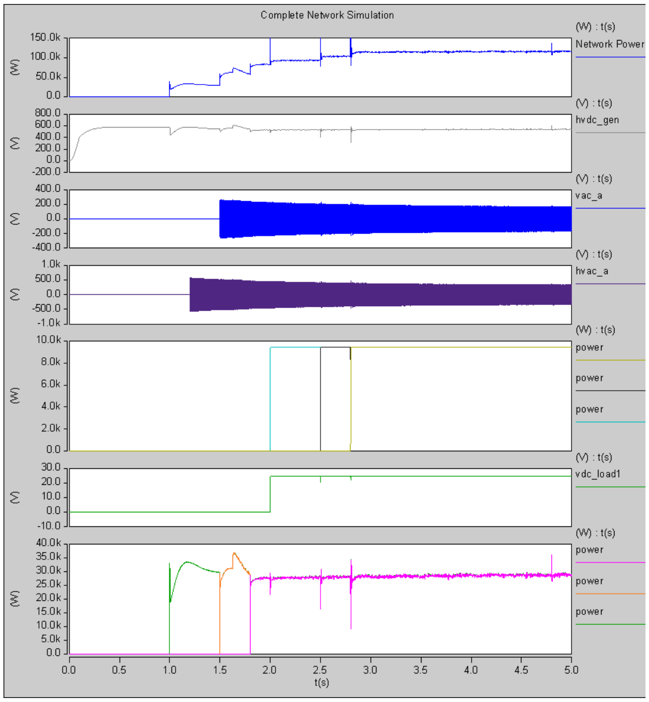

Figure 15: Full Network Simulation Results

10. CONCLUSIONS

This paper has described the techniques used to achieve robust models, using model-based engineering, for the integration of specific equipment models into a complete aircraft network and the validation of their behavior. The paper will provide the results of a complete aircraft power network highlighting how the individual models are integrated into the overall network model. The model creation process has resulted in inherent robustness ensuring effective, accurate and robust simulations.

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